Metastable Fluids

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Executive Summary (~1 page)

Metastable fluid detectors amplify the energy deposited in particle interactions with the stored free energy in a superheated or supercooled liquid target. That amplification can be made selective by matching the different energy-loss mechanisms and length scales for signal and background particles with the relevant phase-change thermodynamics, for example allowing freon-filled bubble chambers to detect few-keV nuclear recoils (e.g. from dark matter scattering) while being completely blind to electron recoil backgrounds. Instrumentation efforts in this area typically focus on (1) extending phase-change based discrimination to new signal regimes, and (2) improving control of spurious phase-change nucleation to enable larger background-free exposures.

The PICO Collaboration uses freon-filled bubble chambers for nuclear recoil detection in targets with high spin-dependent and low spin-independent cross-sections, allowing the exploration of orders-of-magnitude more dark matter parameter space before reaching the "neutrino fog" than can be achieved in noble-liquid targets, which all have very small spin-dependent to spin-independent sensitivity ratios. There is strong physics motivation for freon bubble chambers out to kiloton-year exposures and beyond, but those exposures cannot be achieved without the development of new bubble chamber designs that are more scalable than the current fused-silica chambers, but that maintain (or improve on) current chambers' low spurious nucleation rate. This requires studies of bubble nucleation on surfaces and new bubble-imaging methods (e.g. acoustic imaging). Larger exposures will also require the development of active neutron vetos compatible with the bubble chamber environment.

The SBC Collaboration uses liquid-noble bubble chambers to extend nuclear/electron recoil discrimination to the low energies needed to explore GeV-scale dark matter and coherent scattering (CEvNS) of reactor neutrinos. Like PICO, SBC benefits from pushing boundaries in surface nucleation, but by pushing to higher degrees of superheat rather than to larger superheated volumes. The physics goals of SBC also require calibrations of nuclear recoil sensitivity at energy thresholds an order of magnitude lower (and with absolute energy resolution an order of magnitude finer) than has been previously achieved by bubble chamber experiments. This will involve both the development of new low-energy nuclear recoil calibration schemes, such as Thomson scattering by high-energy gammas and nuclear recoils from gamma emission following thermal neutron capture, and the development of the analysis techniques needed to combine diverse calibration data to constrain nucleation thresholds with O(10) eV resolution.

The Snowball effort aims to detect proton recoils in water, combining a light target with nearly pure spin-dependent coupling to explore spin-dependent interactions of low-mass dark matter. Water is a notoriously difficult fluid to use as a bubble chamber target, but Snowball chambers sidestep this roadblock by supercooling the target rather than superheating it. An entirely new particle detection technology, Snowball chambers face the same instrumentation challenges as SBC and PICO: surface nucleation must be mitigated, and both the threshold and discrimination power of the technique must be calibrated.

Instrumentation requirements to achieve physics goals (list)

- NR/ER discrimination in new regimes
  - with new targets
    - High spin-dependent and low spin-independent sensitivity
    - low mass, kinematically matched to light dark matter
  - at sub-keV thresholds
- Scalability to achieve O(ton-year), and ultimately O(kiloton-year) exposures
- Additional readout modes to improve background discrimination
  - Scintillating targets (e.g. noble liquids)
  - Built-in active vetoes (e.g. scintillating hydraulic baths)
  - Growth of phase change (e.g. ice formation, potentially reflecting directionality)

Significant instrumentation challenges (list)

- Identify and eliminate sources of spurious phase change nucleation both on walls and in the bulk to increase live-time and reduce background.
- Calibration of a threshold detector at very low energy, both for the energy and dE/dx thresholds, as functions of temperature and pressure, and with neutrons, betas, gamams
- Combine disparate modalities (e.g. scintillation + phase change + sound)
- Control of phase change dynamics: need to quench a transition quickly, maximizing livetime and detector stability

Relevant physics areas

- Dark Matter direct detection
  - High-exposure spin-dependent searches (below LXe neutrino fog)
  - Spin-independent 0.1-10 GeV searches to the SI solar neutrino fog
  - Proton scattering (spin-dependent 0.1-10 GeV searches with no neutrino fog, due to the near-zero weak charge of the proton)
- Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)
  - CEvNS measurements on new target nuclei
  - CEvNS measurements with low-energy, high-flux sources (solar, reactor)

Relevant cross-connections (e.g., other topical groups, other white papers)

- CF1
- NF (CEvNS)
- IF8 PRD4 (calibration)

- UF – deep and shallow sites

Further reading (e.g., ref of existing TDR, reference paper, etc.)

https://doi.org/10.1103/PhysRevD.100.022001 (PICO)
https://doi.org/10.1103/PhysRevD.103.L091301 (SBC)
https://doi.org/10.1039/D1CP01083B (Snowball)